

BELLCOMM, INC.

955 L'ENFANT PLAZA NORTH, S.W.

WASHINGTON, D.C. 20024

B70 08025

SUBJECT: Comparison of Advanced Propulsion
Stages - Case 103-8

DATE: August 12, 1970

FROM: C. S. Rall

ABSTRACT

Three variable-size, reusable, in-space propulsion stages are compared on the basis of how much propellant each requires to perform a variety of specified missions. They are assumed to operate from low Earth orbit and return there for reuse. With a few specific exceptions, complete reusability for all systems is maintained. The three stages are a LO_2/LH_2 chemical system, a reusable nuclear stage (RNS) using a solid-core NERVA engine, and an open-cycle gas core nuclear system. The differences among the three systems in the order given are due to increasing inert weights and increasing specific impulses.

On the basis of the assumed stage characteristics, each of the three systems has a range of missions for which it uses the least propellant. In terms of propellant required, payload delivery missions (with zero return payload) to low circular lunar orbit are most efficiently performed by a chemical system if the payload is less than about 10 or 20 Klb, by a solid core nuclear stage for payloads between 20 Klb and 130 Klb, and by a gas core stage if the payload is greater than about 130 Klb. The chemical system generally is applicable to low velocity and low payload missions. The solid core nuclear system uses the least propellant for a range of lunar orbit and synchronous Earth orbit missions, while a gas core system uses the least propellant for manned planetary missions. Maximum propellant capacities at which chemical and solid core system use the least propellant are about 100 and 250 Klb, respectively. These maximum capacities are insensitive to how payload is distributed between the outbound and return payloads. Practicality and sensitivities to stage parameters are not considered in obtaining these applicable payloads and propellant capacities.

Staged modes for the chemical system extend the payload-velocity region in which it uses the least propellant to higher mission velocities. In contrast, staged modes do not increase the region of least propellant usage for the nuclear systems due to their large, fixed, inert weights.

(NASA-CR-113381) COMPARISON OF ADVANCED
PROPULSION STAGES (Bellcomm, Inc.) 23 p

N79-72578

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REF ID: A66011	(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)
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MEMORANDUM FOR FILEINTRODUCTION

Comparisons of the performance of advanced, conceptual propulsion stages have been carried out on the basis of different performance indices. As indicated by Casal,¹ total cost is the desired performance index; but it is very difficult to predict with reasonable accuracy, particularly for conceptual systems. Therefore, a performance index is used which is expected to be closely related to cost. Because it reflects the cost of getting an in-space stage into space as well as the cost of manufacture, the initial mass of a non-reusable system delivering a given payload to a given ΔV has usually been used as the index of performance.

Casal and Schaupp,² for example, use this index. The initial mass is a poor index for a reusable, in-space system, since the transportation costs of propellant to orbit are of major importance. Therefore, the propellant required per mission is the performance index used here.

Three conceptual systems are compared in this memorandum. These are a LO_2/LH_2 chemical system, a solid core nuclear or NERVA system, and a gas core system. The nuclear systems, of course, use LH_2 as propellant. Each system is rubberized or sized to the job expected of it according to a scaling law. The comparison is carried out by dividing a plot of one-way ΔV versus the discretionary payload into regions in which each system uses the least propellant. These regions are dependent on the specific impulses and the scaling laws assumed. It is conceivable that with other scaling laws and specific impulses a region of least fuel consumption could be greatly reduced in size or even eliminated.

OPERATING MODES

The operating modes of a reusable stage can be much more complicated than those of a disposable injection stage due to additional mission operations. Reusability requires that the stage return to low Earth orbit for refueling and the attachment of the next payload or payloads.

A mission is assumed to consist of two legs: an outbound leg and a return leg. Each leg is assumed to require half of the total ΔV of the mission. Half way through the mission, at the end of the outbound leg, payload may be dropped. Additional payload may be carried for the entire round trip. This mission profile is very general, because it can be representative of missions between low Earth orbit and high Earth orbit, of round-trip missions to the Moon or the planets, and of transplanetary injection missions in which payload is accelerated to a desired injection velocity after which the injection stage is returned to low Earth orbit. One should note that nothing is assumed about the total number of engine burns in the mission; only the half and half distribution of the mission ΔV is supposed.

In this memorandum, three different distributions of payload are allowed. The first distribution is a payload delivery mission in which all of the payload is delivered to the one-way ΔV (half of the total ΔV); no payload is returned. Such a payload delivery mission is what would be used to launch a spacecraft on its way to another planet or to deliver material to lunar orbit. The second distribution of payload adds an additional round-trip payload of 20 Klb to the payload delivered to the one-way ΔV . 20 Klb could very well represent a crew capsule. The third distribution drops off no payload at the one-way ΔV point but instead carries the entire payload through the complete mission. This last mission is also characteristic of using the stage in a disposable fashion wherein the stage delivers the payload to twice the one-way ΔV .

For most of the plots of this memorandum, the use of one stage for each system is assumed. However, staged modes are also considered for the chemical and the solid core propulsion systems. The use of one stage only is called here the Standard Mode and is indicated by the first sketch in Figure 1. The less complex staged mode considered is known as Mode A after work

performed by Skeer for Reference 3, and is indicated by the second sketch in Figure 1. Two equal stages are used with this mode. The first stage delivers the second stage and the payload(s) to the staging velocity and returns to low Earth orbit, depleted of propellant. The second stage delivers the one-way payload to the one-way ΔV and returns to low Earth orbit with the round-trip payload. Mode B, also after Skeer's work in Reference 3, is the more complex staged mode considered and is indicated by the third sketch in Figure 1. It is similar to Mode A with the addition that the refueled first stage or a third equal stage goes out to retrieve the empty second stage and any round-trip payload. The staging point between the second and third stages must be less than the one-way ΔV ; to meet this Mode B requirement at low ΔV 's and low round-trip payloads, the third stage (or refueled first stage) propellant must be offloaded.

GRAVITY LOSS

Gravity loss, which is due to finite thrust levels on the stages considered, is not directly calculated in this memorandum. Accurate computation of the gravity loss, of course, requires a specific mission and numerical integration of the various thrusting periods in it.

For this investigation, concern with gravity loss is restricted to differences in the losses associated with the different systems. They are expected to be a small part of the total ΔV required for most missions. It is also anticipated that at points of comparison, the NERVA system (using a single engine) will have the lowest initial thrust to weight and hence the highest gravity loss of any of the three systems. To maintain small gravity losses, a chemical propulsion system would either increase engine thrust or the number of engines. With the small stages and payloads considered for the gas core at points of comparison with the solid core, the assumed gas core thrust of about 300 or 400 Klb results in high thrust to weight ratios and small gravity losses. Large gas core stages, however, would have large gravity losses due to lower thrust to weight ratios.

A method of penalizing the NERVA stage for its expected higher gravity losses at points of comparison with the other systems is to add some small percentage to the ΔV required. This has the same effect as reducing the specific impulse by the same small percentage. The small percentage used by Johnson and Skeer⁵ to penalize a NERVA stage on a lunar mission is only about 2%. The only account taken of gravity loss in this memorandum is to set the NERVA specific impulse at a lower value (825 sec) than might be expected for the time frame of interest. This penalty is reasonable if most of the thrusting periods occur in strong gravity fields such as near the Earth (that is, for mission departure and return).

SCALING LAWS

Scaling laws are chosen for the three reusable systems on the basis of several design studies. These relationships define the total inert weight and the total weight of the stage as a function of the propellant carried by the stage. The three scaling laws are indicated in Figure 2 by plots of the stage inert weight as a function of the usable propellant carried.

For each system, the inert weight includes tankage and structure, an engine, a meteoroid shield, thermal insulation, unusable propellant residuals, and a radiation shield for the nuclear stages. For a given propellant weight, a higher inert weight is expected for the reusable stages considered here than for an injection stage, because of the requirements for a meteoroid shield and thermal protection for in-space storage capability. A reusable engine might also be somewhat heavier than a non-reusable one. Reusability may require a somewhat larger radiation shield on the nuclear stages than would otherwise be required.

The chemical, cryogenic stage is fueled with liquid hydrogen and liquid oxygen and has a specific impulse of 460 sec. W_i , the inert weight of the stage, is assumed to be given by

$$W_i = 0.15 W_p \quad (1)$$

where W_p is the mass of the propellant. This scaling law gives a constant mass fraction λ of 0.87. Reference 3, a study of the SIVB for modification as a reusable, in-space stage, contains the data for the small area labeled by a 1 in Figure 2. The basic, unmodified SIVB stage inert weight contributes about $0.122 W_p$ to the above amount. Calculations based on the study by Johnson and Skeer⁴ indicate that if a meteoroid shield weight of $0.013 W_p$ is allowed, then it may be possible to provide 5 years protection with a probability of no penetrations equal to 0.99. These numbers assume an Earth or lunar orbit environment and an advanced bumper design (bumper factor of 13). A less optimistic factor would mean that the same probability of no penetrations could be supplied for fewer years.

The NERVA stage is assumed to be fueled by liquid hydrogen and to have a specific impulse of 825 sec, a value that is achievable now. Higher specific impulses may be expected in the future, but 825 sec is used here to compensate for gravity losses. Stage inert weight is assumed to be given by

$$W_i = 50 \text{ Klb} + 0.15 W_p \quad (2)$$

The mass fraction λ of this stage is not constant because of the constant in Equation 2. Areas labeled by the numerals 2, 3, and 4 in Figure 2 indicate the range of weights determined by Lockheed Missiles and Space Company,⁶ McDonnell Douglas,⁷ and North American Rockwell⁸ respectively. These studies included meteoroid and thermal protection, but the radiation protection included is probably inadequate, and additional radiation shield weight might reasonably be expected. With the same assumptions as for the chemical stage, a meteoroid shield weighing $0.065 W_p$ is included in the equation above. The larger weight required for the RNS meteoroid shield is due to the low density and correspondingly large volume of hydrogen fuel as compared with the density and volume of the chemical system propellants.

The gas core nuclear stage is assumed to have a specific impulse of 1800 sec. A reasonable estimate for the weight of the gas core engine is 300 Klb for a thrust of about 300 or 400 Klb according to Ragsdale.⁴ The large, fixed gas core engine size is assumed, because although it is believed possible to build one with a lower thrust, it does not appear feasible to build a high I_{sp} open-cycle gas core engine that weighs much less. The inert weight of the gas core stage is taken as

$$W_i = 325 \text{ Klb} + 0.15 W_p \quad (3)$$

STANDARD MODE RESULTS

Figures 3, 4, and 5 divide the plot of ΔV versus discretionary payload into regions in which each of the three systems is "best" in terms of the least fuel used. At each point on a boundary between two regions, each system (accurately sized) can perform the mission for the same amount of propellant. In each of the three regions, dotted lines of constant propellant quantity indicate the performance of the given size stage. The numbers indicate thousands of pounds of propellant. Inert weight and hence the total mass of a stage with a given propellant quantity may be determined from the scaling laws given in Figure 2 or Equations (1)-(3).

Three different figures are necessary because of the three different ways used here to define the discretionary payload indicated by the vertical scale. In Figure 3, the discretionary payload is carried one way, and no payload is carried on the return trip. Discretionary payload is also carried one way, in Figure 4; but 20 Klb (in addition to the discretionary payload) is carried for the round-trip. In Figure 5 the variable payload is carried for the round-trip; zero additional payload is carried on the outbound leg. Each point in the figures defines a mission in terms of the one-way ΔV , the one-way payload, and the round-trip payload. Only the Standard Mode was assumed in defining the regions in Figures 3 through 5.

Ranges of ΔV 's for several representative missions are shown by bars at the bottom of each of Figures 3 through 8. The bars are presented for purposes of comparison, but the plots are general and assume little about the mission performed. The bars assume that the vehicle starts in low circular Earth orbit (LEO), accelerates to the ΔV specified in one or more burns of the engine, may or may not drop payload, and then accelerates through the same ΔV , usually to return to LEO with or without payload. All vehicles are returned empty to LEO for refueling and reuse, except for the transplanetary injection missions of Figure 5 where the vehicle is disposed of after use. The ΔV 's indicated by the bars were obtained from References 9 through 13.

The lower end of the bar for the lunar orbit missions assumes the lunar orbit to be a highly eccentric, 24 hour period, low periapse orbit about the Moon, while the upper end of the bar assumes a mission to a low circular lunar orbit. Little ΔV is assumed in this bar for plane change.* However, large plane changes are possible at the moon or at the Earth for small ΔV 's by making the plane changes in a highly eccentric orbit.¹⁴ After changing planes, a vehicle can be maneuvered into a low circular orbit about the Moon. Payload delivered to lunar orbit might be expected to include lunar surface payload and a lunar lander or fuel for a lander that is already in lunar orbit.

The synchronous orbit missions indicated take place between LEO and synchronous Earth orbit. The variation in ΔV indicated by the bar is due to differences in inclination (of 0° to 45°) between synchronous orbit and LEO.

Planetary injection missions involve launching a payload onto a trajectory to another planet and then immediately retrofiring to remain captured at Earth. Such a mission may involve several intermediate elliptical orbits during launch from LEO and retrieval of the stage back into LEO in order to keep the gravity losses small.¹⁵ Variation in injection ΔV 's to Mars are due primarily to variations with the year of the opportunity. Variation in injection ΔV to Jupiter is

*The upper end of the bar allows 1.4 Kft/sec for plane change, gravity loss, and a somewhat faster Earth-Moon trip, while the lower end of the bar allows none of these. No plane change impulsive transfer between a 24 hr ellipse and a low circular orbit at the Moon accounts for 1.8 Kft/sec.

due primarily to the length of time allowed for interplanetary passage. The payload for manned planetary missions would include probes, a mission module for the crew, landers, and propulsion stages for the remainder of the mission following transplanetary injection.

No payload is carried round-trip on planetary injection missions; the purpose of the return leg is the retrieval of the stage. Figure 3 applies to such missions. Figure 5, which considers all of the payload to be carried for the round-trip, is unrealistic for transplanetary injection missions. It can be made meaningful, however, if the vehicle is to be used in a disposable mode. (Even a reusable vehicle may be discarded after the last mission of its useful life.) In this mode the vehicle accelerates itself and the payload to the desired velocity (twice the one-way ΔV) and is then abandoned; it does not return to LEO. Therefore in Figure 5, the ΔV 's indicated by the transplanetary injection bars have been halved, as compared with those in Figure 3.

Each of the three systems has some degree of applicability to lunar and synchronous orbit missions. On missions to low circular lunar orbit and zero-plane-change synchronous orbit missions, the chemical system requires the least propellant to deliver payloads less than 10-20 Klb. A chemical system uses less propellant than nuclear systems on highly eccentric lunar orbit missions for one-way payloads up to 50 Klb or round-trip payloads up to 14 Klb. The chemical stage size corresponding to these payloads has a capacity of slightly over 100 Klb of propellant.

On missions to low lunar orbit and zero-plane-change synchronous orbit missions the solid core system uses less propellant than the gas core system for one-way payloads up to 130 Klb and round-trip payloads up to 50 Klb. The propellant capacity for the NERVA stage carrying these payloads is about 250 Klb.

Lunar and synchronous orbit missions requiring larger payloads are performed most efficiently by a gas core stage.

Transplanetary injection missions can also make effective use of each of the three systems. A chemical system requires the least propellant to inject up to 10 to 40 Klb (depending on year of opportunity) through transplanetary injection on low energy missions to the

near planets. In the disposable mode, low energy transfers to Jupiter and difficult missions to the near planets are accomplished best by the chemical system for payloads up to 10 or 15 Klb. In the reusable mode, the solid core system can be used to advantage for low energy transplanetary injections of up to about 160 Klb to the near planets. This stage corresponds to about 250 Klb propellant; when used in the disposable mode it can inject about 310 Klb of payload.

The optimum missions for the chemical system are characteristic of unmanned missions, considering the range of payloads (less than 10 - 40 Klb). Optimum missions for the solid core system represent very ambitious unmanned missions. Large transplanetary injection payloads of greater than 200 Klb are characteristic of manned missions and are best delivered by a gas core system.

For a given amount of propellant and a given ΔV , the choice of the type of propulsion is generally independent of the distribution between one-way and round-trip payloads. This fact is evident from Figures 3-5 because the intersection of a propellant curve (signifying a given stage size) with a boundary curve (between regions of least propellant usage) always occurs at about the same ΔV regardless of the different payload distributions.

RESULTS IN MODES A AND B

Figures 6 and 7 compare the chemical and solid core systems when the chemical system is operated in Modes A and B respectively, while the RNS operates only in the Standard Mode. The payload distribution used is the same as that in Figure 4 (variable one-way plus 20 Klb round-trip); and therefore, Figures 6 and 7 should be compared with Figure 4 to determine the effect of using the different modes. The lines of constant propellant quantity given in Figures 6 and 7 require some explanation. They refer to the total propellant used for the mission. (Note that they never refer to the gas core system.) For the chemical system used in Mode A, the quantity of propellant indicated by a dotted line (beneath the chemical-solid core boundary) must be divided by two in order to obtain the propellant capacity of each of the two identical chemical stages used. In like manner, the propellant indicated for the chemical system in Mode B must be divided by three to obtain the capacity of the typical stage. The lines of constant propellant quantity

in the solid core region on these plots do not extend to higher velocities because of the basic limitations of the solid core stage. No matter how big the stage becomes, it can never supply a one-way ΔV of greater than 27.2 Kft/sec with the stage parameters assumed here. Although the gas core system is not considered in these plots, the dividing line between the solid core and the gas core systems, as well as the chemical-solid core boundary from Figure 4, are retained for comparison as dashed and dotted lines.

On comparison with Figure 4, Figures 6 and 7 demonstrate that Modes A and B respectively do extend the maximum ΔV over the standard mode. A large advantage is shown for Mode B. Mode B makes the chemical system applicable to low circular lunar orbit and zero-plane change synchronous orbit missions for payloads of up to 30 Klb delivered (plus 20 Klb round-trip). In fact, its region of applicability extends beyond that of the solid core region at high ΔV 's and small payloads.

One should note from Figures 6 and 7 that the chemical system, particularly in Mode B, has been extended to larger total propellant loadings as well as to larger one-way ΔV 's by the use of the staged modes. However, one must divide by two and three respectively to determine the propellant loading of the typical stage in Modes A and B. With this fact in mind, one can see that with the 20 Klb round-trip payload requirement, the maximum applicable chemical stage propellant capacities are about 80 Klb in the Standard Mode, 60 Klb in Mode A, and 180 Klb in Mode B. At greater propellant loadings than three times the Mode B figure above, the nuclear systems are more economical in terms of propellant usage because of their higher specific impulse and their improved propellant mass fraction at large propellant loadings.

Figure 8 contains regions of least propellant usage for all three systems. The chemical and solid core systems operate in Mode A, while the gas core system operates in the Standard Mode. As in Figures 4, 6, and 7, 20 Klb of payload is carried round-trip in addition to the discretionary delivered payload indicated by the vertical scale. The two boundary lines separating the three regions in Figure 4 are retained for comparison as dashed and dotted lines. Note that the region in which the solid core uses the least fuel is much smaller than it is in Figure 4. Use of Mode A by the solid core system does not increase the maximum applicable ΔV at which the solid core uses the

least fuel and reduces the maximum applicable payload at smaller ΔV 's. Comparison of the chemical-solid core boundary in Figure 8 with that in Figure 6 demonstrates that solid core use of Mode A reduces the efficiency of the solid core system. In short, use of the staged Mode A degrades the performance of the solid core nuclear system due to the large fixed weight of such stages. With staged modes, smaller stages are used and the fixed weights account for a greater fraction of stage weight resulting in lower performance stages.

In addition to being the only one of the three systems that benefit from use of staged Modes A and B, the chemical system is suitable for direct lunar landing missions. Nuclear systems on a lunar orbit mission must carry a chemical lunar landing vehicle. If the thrust-to-weight ratio of a chemical stage is not sufficient, it can be augmented by additional engines more easily than with nuclear systems. Some additional weight penalty would also be incurred for landing gear. Figure 7 shows that the region of least propellant usage by chemical Mode B approaches the 21.5 Kft/sec necessary for a lunar landing mission.

CONCLUSIONS

Each of the three reusable systems considered here, the hydrogen-oxygen chemical system, the solid core nuclear system, and the gas core nuclear system, has a payload - ΔV region of minimum propellant consumption. As might well be expected, the regions of least fuel consumption are ordered, chemical - solid core - gas core as one goes from low payloads and/or velocities to high payloads and/or velocities.

Low circular lunar orbit missions, no plane-change synchronous Earth orbit missions, and transplanetary injection missions to the near planets at favorable opportunities have similar ΔV requirements. For placement of small payloads the chemical system in the reusable mode is marginally suitable. In the disposable mode, it is suitable for placement of payloads of up to about 30 Klb. The maximum size for which the chemical system is most economical is about 100 Klb of propellant capacity. The most economical solid core nuclear system stage size ranges between about 100 and 250 Klb of propellant capacity. The payloads applicable to the RNS are, of

course, much larger (up to the order of 130 Klb delivered or 50 Klb carried round-trip) than those applicable to the chemical system. For missions requiring still larger payloads and/or velocities, gas core systems use the least propellant.

It should be noted that as one goes to larger payloads and correspondingly larger propellant capacities with nuclear systems, the amount of propellant required to deliver a pound of payload to a given ΔV goes down. For chemical systems, however, the amount of propellant required per pound of payload is constant due to the scaling law assumed (that is, zero fixed weight in Equation (1)).

Staged Modes A and B can be used to move small payloads to higher velocities than possible with a single stage chemical system. Nuclear systems do not benefit from use of the staged modes because of the large fixed weights in their scaling laws.

The range of propellant capacities suggested by this memorandum can be compared with some propellant capacities of systems that are being considered. A space tug with a propellant capacities of about 44 Klb, is well within the maximum applicable capacity of about 100 Klb for chemical systems. An SIVB which could be modified for use as a reusable in-space stage has a propellant capacity of 233 Klb. This falls outside the applicable region for chemical systems used in the Standard Mode. The assumed gas core system characteristics, in comparison with the solid core characteristics, suggest a maximum solid core RNS propellant capacity of 250 Klb, which compares with presently proposed capacities near 300 Klb. This disagreement in capacity is academic because the gas core-solid core boundary is based on poorly defined gas core system characteristics (i.e., the gas core system is no more than a concept).

Each of the three systems considered here has been shown to have a suitable role in the spectrum of missions considered.

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1013-CSR-klm

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Attachments
Figures 1-8

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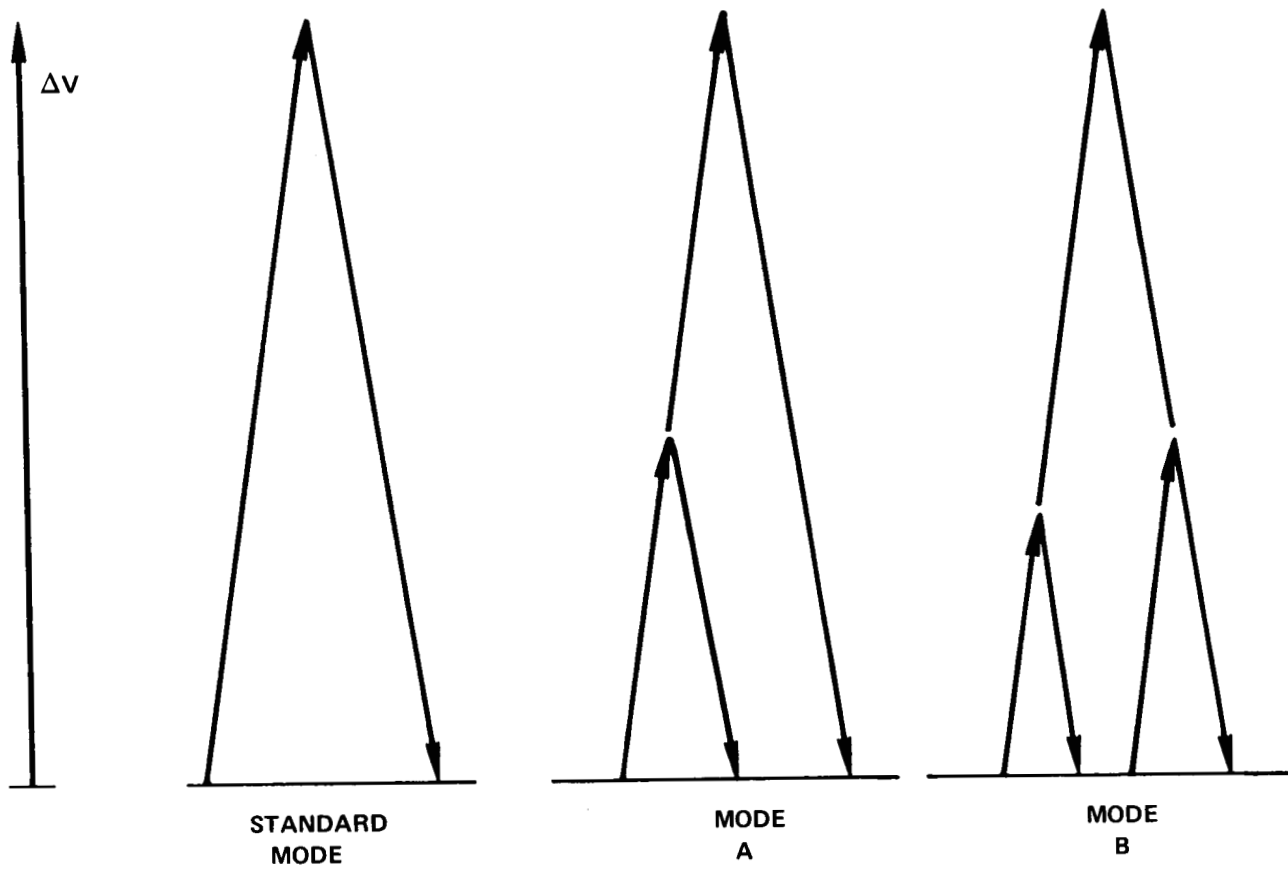


FIGURE 1 - OPERATING MODES

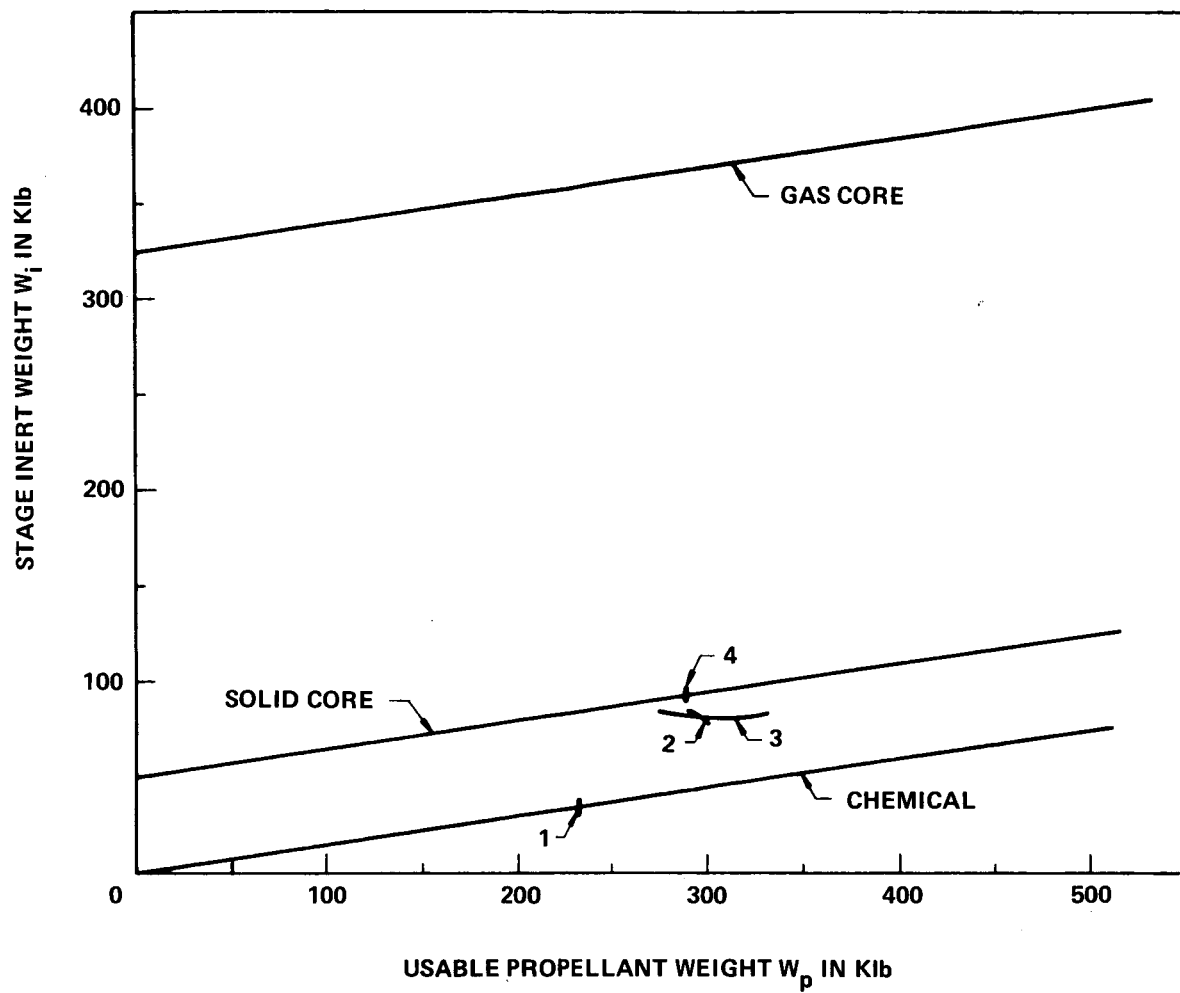
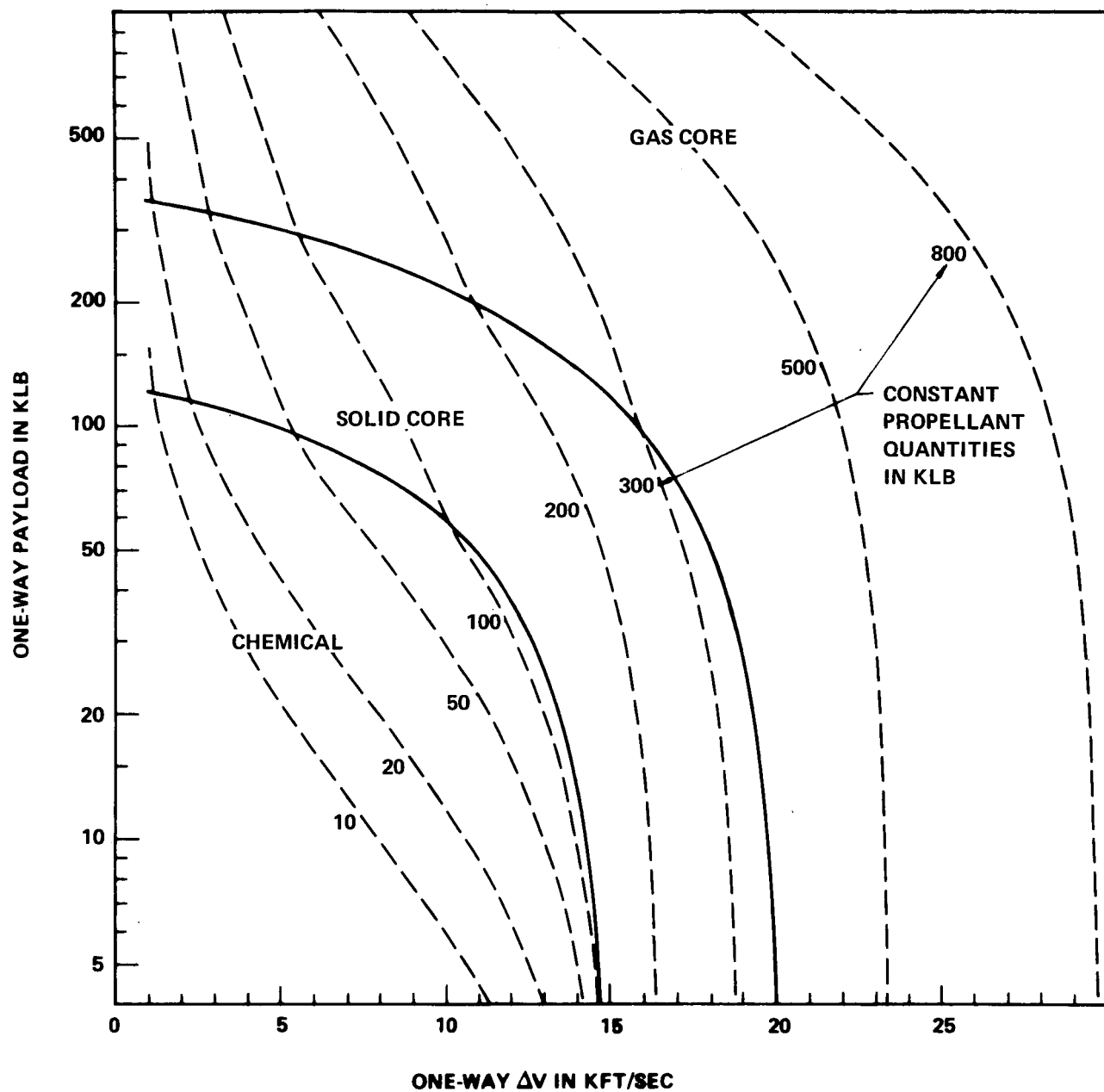


FIGURE 2 - SCALING LAWS



LUNAR AND EARTH ORBIT MISSIONS:

———— LUNAR ORBIT

———— SYNCHRONOUS EQUATORIAL

TRANSPLENETARY INJECTION MISSIONS:

MARS CONJUNCTION MISSION ————

VENUS FLYBY TO MARS ————

360 DAY MISSION TO MARS ————

JUPITER AND JUPITER FLYBY TO OUTER PLANETS ————

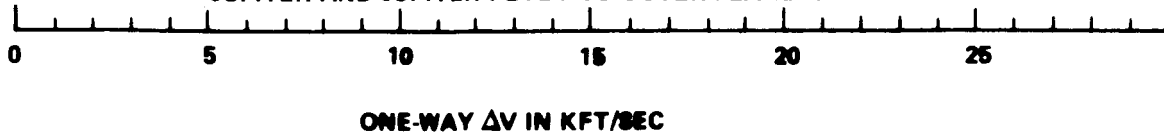
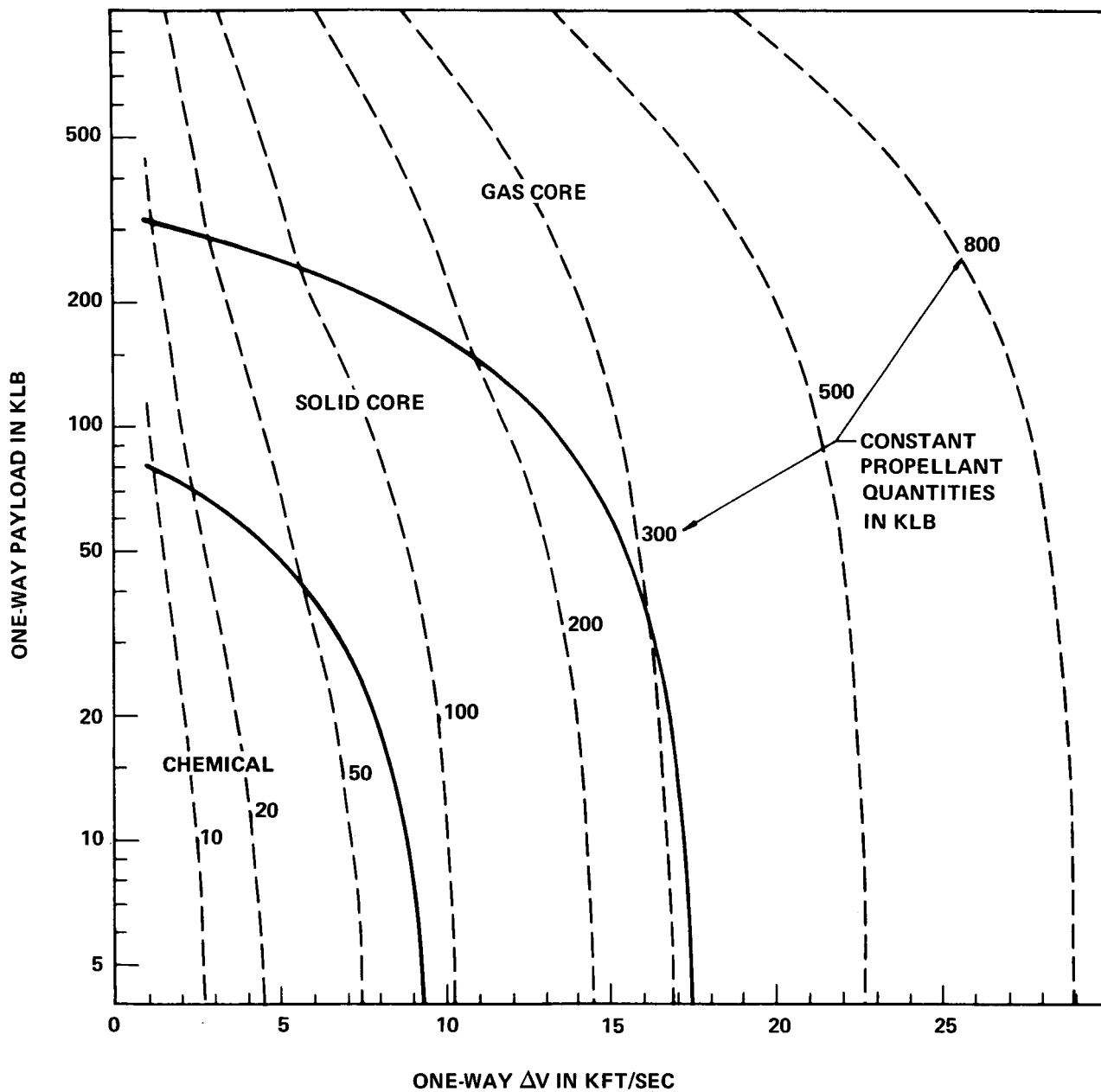


FIGURE 3 - VARIABLE OUTBOUND PAYLOAD - NO RETURN PAYLOAD



LUNAR AND EARTH ORBIT MISSIONS:

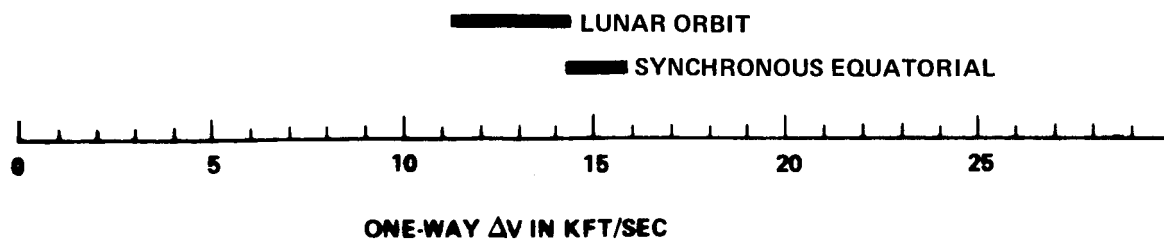
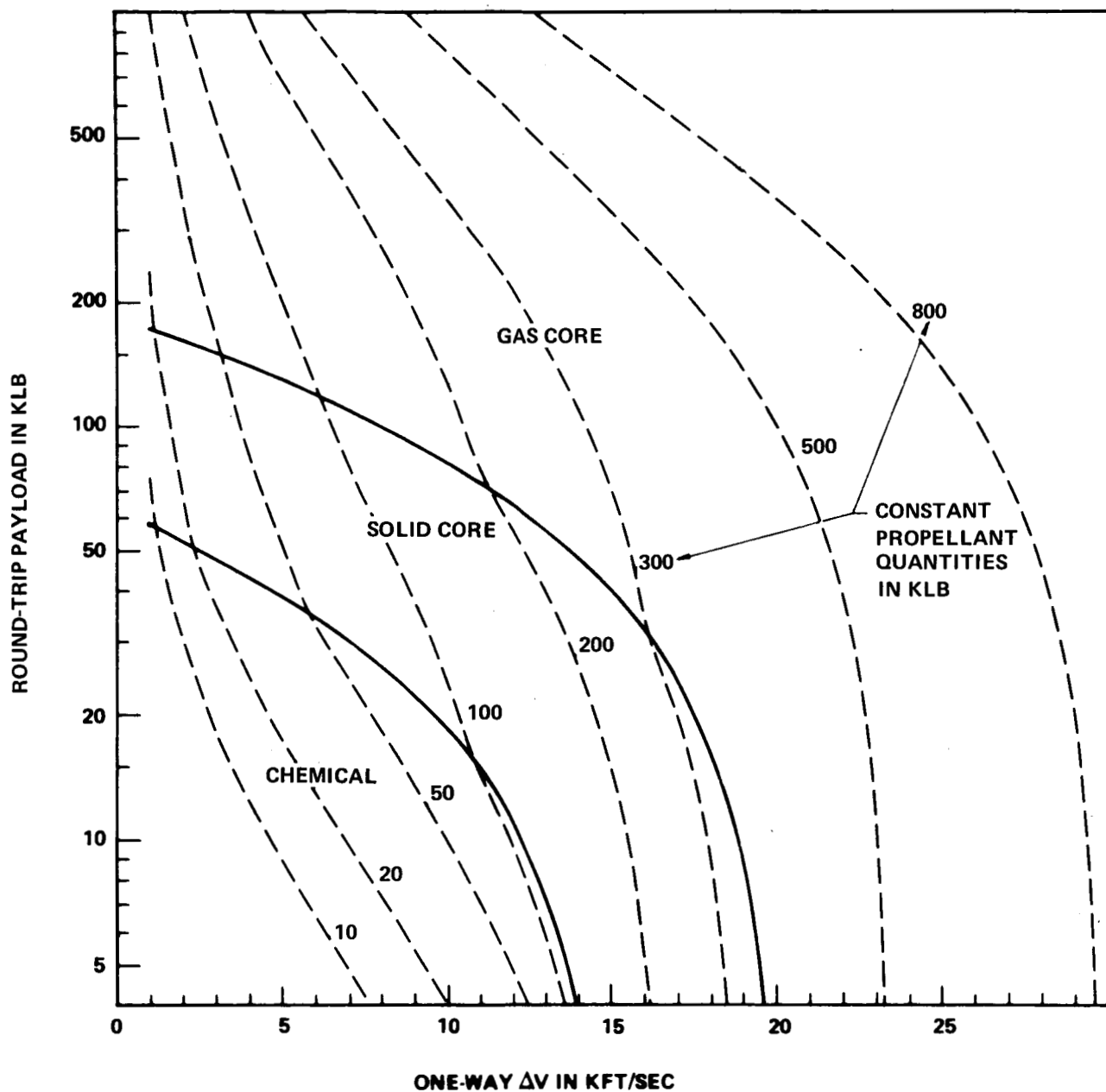


FIGURE 4 - VARIABLE OUTBOUND PAYLOAD - 20 KLB ROUND TRIP



LUNAR AND EARTH ORBIT MISSIONS:

———— LUNAR ORBIT

———— SYNCHRONOUS EQUATORIAL

TRANSPLANETARY INJECTION MISSIONS* (DISPOSABLE MODE):

■ MARS CONJUNCTION MISSION

■ VENUS FLYBY TO MARS

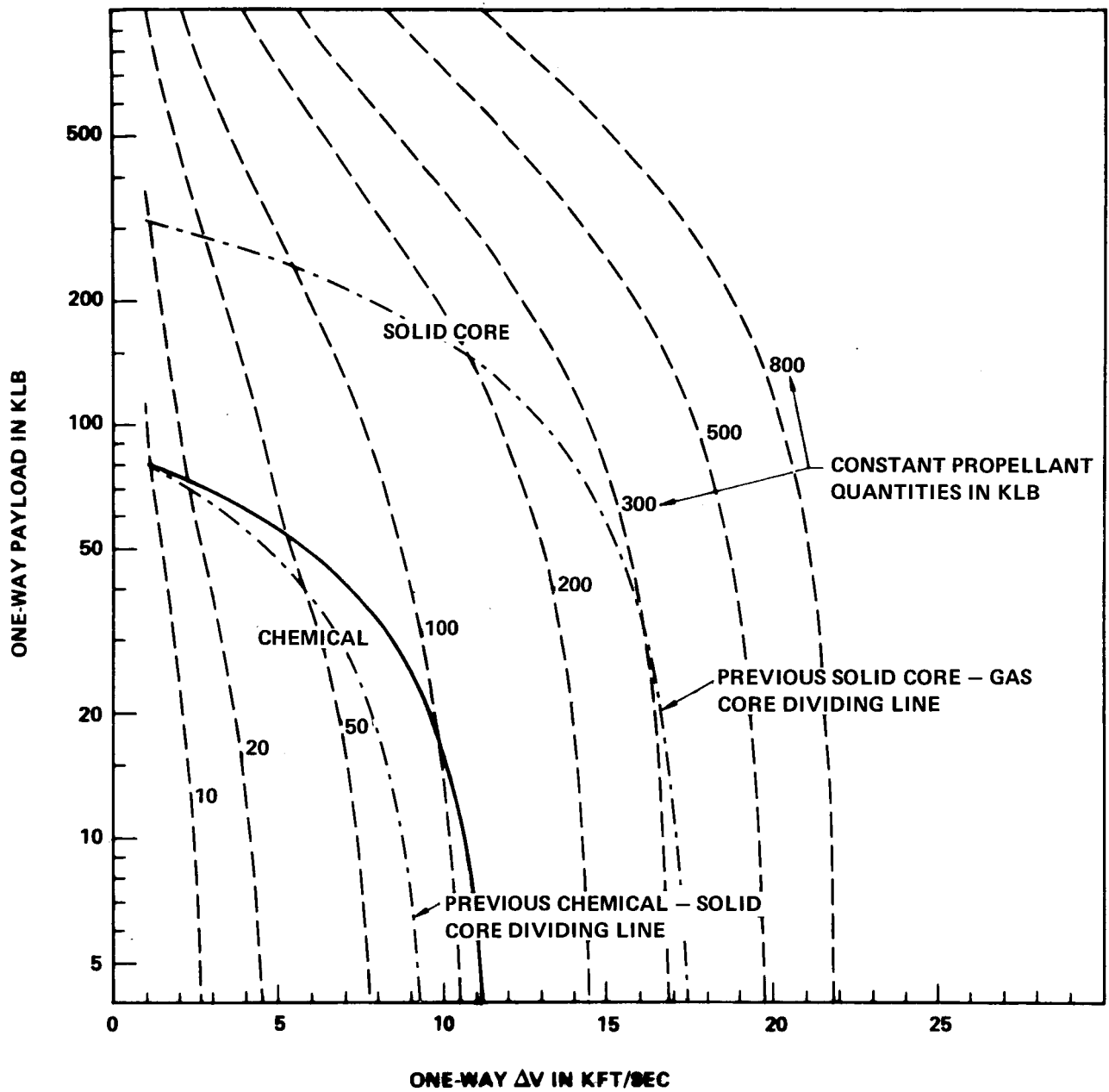
———— 360 DAY MARS

JUPITER AND FLYBY —————



FIGURE 5 - VARIABLE ROUND-TRIP PAYLOAD

*ONE HALF OF THE TOTAL MISSION ΔV IS INDICATED BELOW (SEE TEXT).



LUNAR AND EARTH ORBIT MISSIONS:

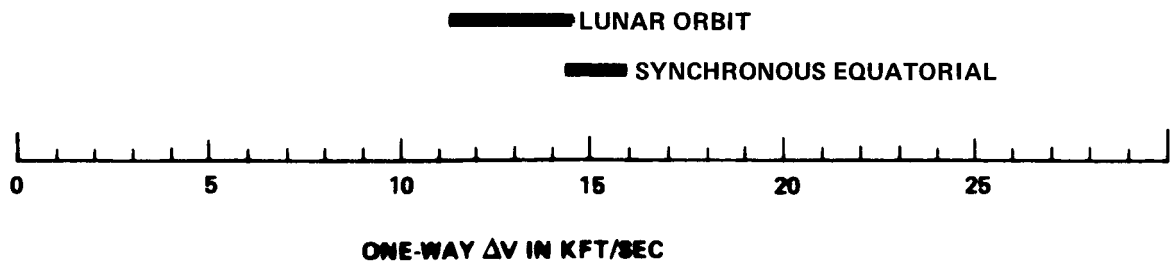
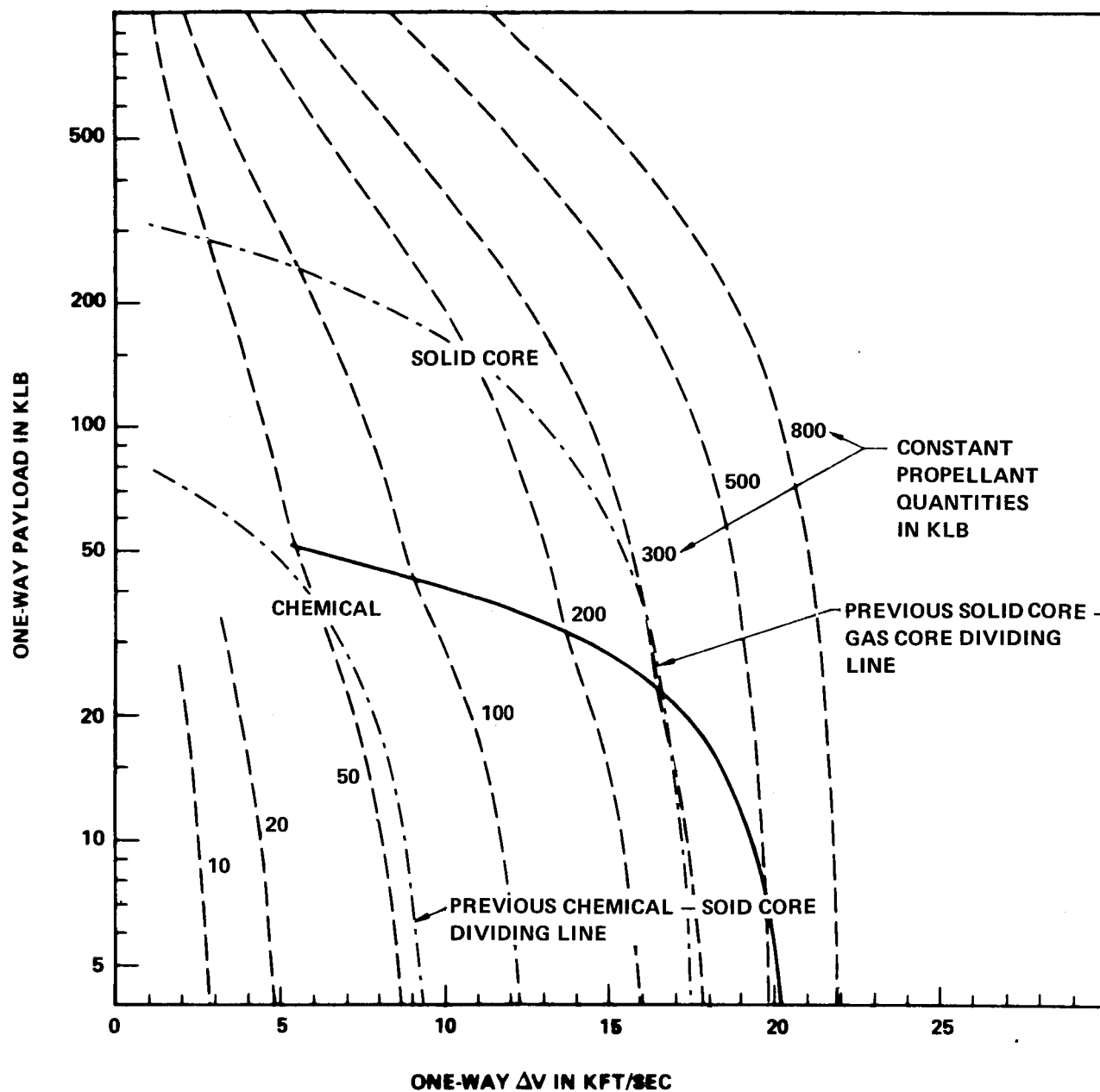


FIGURE 6 - VARIABLE OUTBOUND PAYLOAD WITH CHEMICAL MODE A -
20 KLB ROUND TRIP



LUNAR AND EARTH ORBIT MISSIONS:

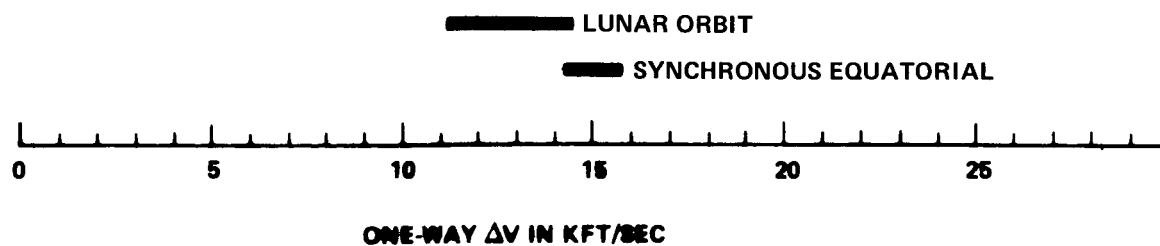
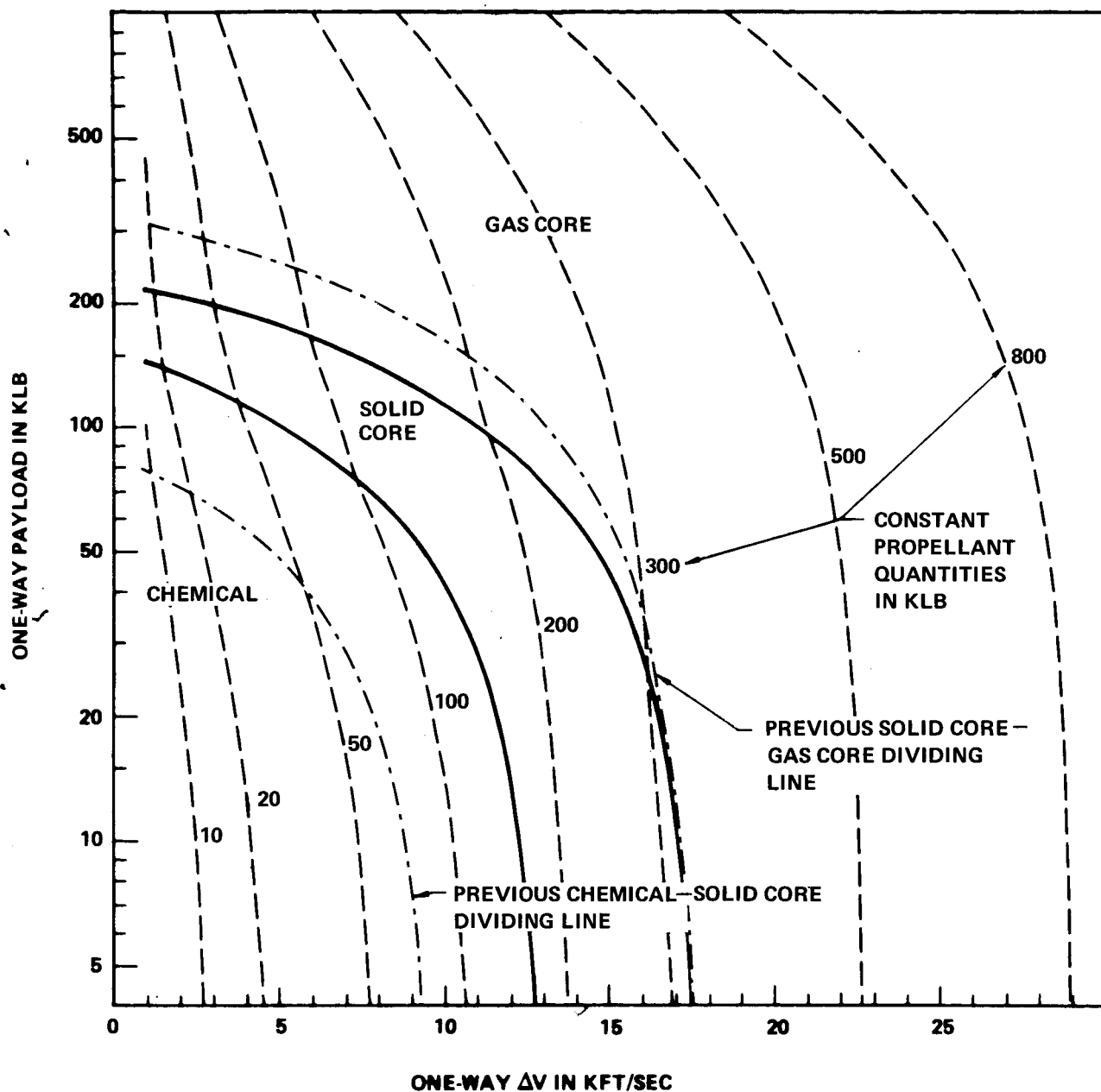


FIGURE 7 - VARIABLE OUTBOUND PAYLOAD WITH CHEMICAL MODE B -
20 KLB ROUND TRIP



LUNAR AND EARTH ORBIT MISSIONS:

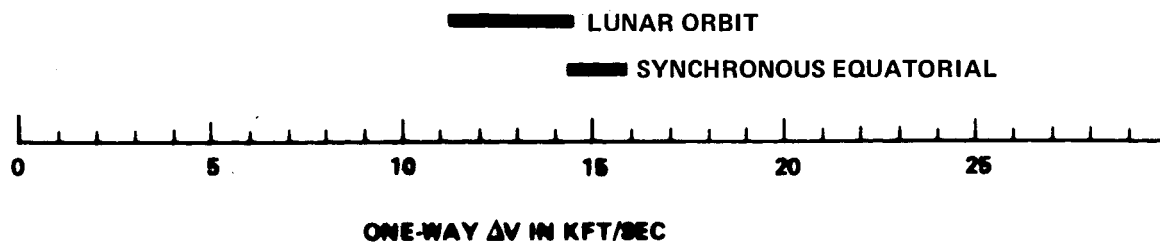


FIGURE 8 - VARIABLE OUTBOUND PAYLOAD WITH CHEMICAL AND SOLID CORE MODE A - 20 KLB ROUND TRIP

BELLCOMM, INC.

Subject: Comparison of Advanced Propulsion
Stages - Case 103-8

From: C. S. Rall

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